

并网变流器全工况阻抗模型的黑箱辨识方法

赵崇滨, 姜齐荣

(电力系统及发电设备控制与仿真国家重点实验室(清华大学电机工程与应用电子技术系), 北京 100084)

摘要: 阻抗分析法因适用于并网变流器控制结构和参数均未知的黑箱系统, 已成为工程中评估宽频振荡风险的重要选择。以跟网型三相两电平变流器为例, 首先, 使用谐波线性化方法, 严格推导了计及直流侧耦合的交流侧全工况开/闭环理论阻抗模型, 实现了模型参数与工作点高阶项的完全解耦。其次, 依据理论模型特征, 明确了黑箱辨识方法的基本原理, 分析了辨识单一开/闭环阻抗模型频率响应所需的工况数量。使用辨识得到的全工况阻抗模型, 实现了不同短路比条件下系统安全运行域的快速评估, 并通过时域仿真验证了其准确性。此外, 讨论了所提方法的合理性、普适性以及相对于深度学习方法的优越性, 为阻抗分析法的实际应用提供了参考。

关键词: 阻抗分析法; 黑箱系统; 模型辨识; 全工况; 稳定性分析

Black-box identification of a full operating condition impedance model of grid-tied converter

ZHAO Chongbin, JIANG Qirong

(State Key Lab of Control and Simulation of Power Systems and Generation Equipment,
Department of Electrical Engineering, Tsinghua University, Beijing 100084, China)

Abstract: Impedance-based analysis has become an important choice for engineering for evaluating the risk of broadband oscillation. This is because it adapts to the black-box system with unknown parameters or control structure of grid-tied converters. In this paper, the grid-following three-phase two-level converter is taken as an example. First, using harmonic linearization, the open/closed-loop theoretical full operating condition AC impedance model (IM) considering the DC coupling is rigorously deduced. In particular, the model parameters and the high-order terms of operating points are fully decoupled. Secondly, based on the features of the theoretical model, the basic principle of the black box identification method is clarified, and the numbers of operating conditions for identifying a single frequency response of the open/closed-loop IM is analyzed. Using the identified full operating condition IMs, rapid evaluation of the safe operation area of the system under various short-circuit ratios is realized, and the accuracy is verified by time domain simulations. In addition, the rationality and universality of the proposed method as well as its superiority over deep learning methods are discussed. This provides a reference for the practical application of the impedance-based method.

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Key words: impedance-based analysis; black-box system; model identification; full operating condition; stability analysis

0 引言

风电、光伏等新能源经电力电子变流器接入新型电力系统引发的宽频振荡问题(小信号稳定性问题, 简称稳定问题)已受到学术界和工业界的广泛关注^[1-6]。大量研究表明, 对组件结构、参数已知的白箱系统, 使用状态空间或传递函数均能够有效分析

其稳定问题^[7]; 对变流器控制结构已知、参数未知的灰箱系统或控制结构、参数均未知的黑箱系统, 难以保留全部状态变量建立状态空间^[8], 但基于量测的传递函数频率响应仍可有效分析系统的稳定性。

使用电压-电流小信号构建的阻抗/导纳模型已成为支撑实际工程稳定性分析的实用工具。对常用的三相两电平变流器, 阻抗建模技术已较为成熟^[9], 一个重要的结论是受闭环控制影响, 变流器阻抗模型随系统潮流的变化而变化, 因此全工况(指端口电压-电流在设定范围内的组合)黑箱系统的稳定性评

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量(由左至右), 且稳态矢量与小信号矢量存在 $(f_1 - f_p)$ 的频移 (f_1 为 50 Hz 基波频率)。 $\Delta \mathbf{m}_a$ 由控制回路决定, 如式(4)所示。

$$\Delta \mathbf{m}_a = k_{\text{pwm}} [\mathbf{Q}(s)\Delta \mathbf{i}_a + \mathbf{P}(s)\Delta \mathbf{v}_a + \mathbf{E}(s)\Delta \mathbf{v}_{\text{dc}}] \quad (4)$$

式中: k_{pwm} 为调制系数, $k_{\text{pwm}} = 1/u_{\text{dc}}^*$; 传递函数矩阵 $\mathbf{Q}(s)$ 、 $\mathbf{P}(s)$ 和 $\mathbf{E}(s)$ 描述了对应矢量间的多输入-多输出关系, 如式(5)所示。

$$\begin{cases} \mathbf{P}(s) = -\{\mathbf{T}(\cos(\theta))[\mathbf{T}(\mathbf{e}_q) + \mathbf{H}_{\text{cc}}(s)\mathbf{T}(\mathbf{i}_q)] + \\ \quad \mathbf{T}(\sin(\theta))[\mathbf{T}(\mathbf{e}_d) + \mathbf{H}_{\text{cc}}(s)\mathbf{T}(\mathbf{i}_d)]\} \mathbf{G}_{\text{pll}}(s) \\ \mathbf{Q}(s) = 2\mathbf{T}(\cos(\theta))[-\mathbf{H}_{\text{cc}}(s)]\mathbf{T}(\cos(\theta)) + \\ \quad 2\mathbf{T}(\sin(\theta))[-\mathbf{H}_{\text{cc}}(s)]\mathbf{T}(\sin(\theta)) \\ \mathbf{E}(s) = \mathbf{T}(\cos(\theta))\mathbf{H}_{\text{cc}}(s)\mathbf{H}_{\text{dc}}(s) \end{cases} \quad (5)$$

$$\begin{cases} \cos(\theta) = [0.5, 0, 0.5], \sin(\theta) = [j0.5, 0, -j0.5] \\ \Delta \theta = -2[\mathbf{I} + \mathbf{H}_{\text{pll}}(s)\mathbf{T}(\mathbf{u}_{\text{cd}})]^{-1} \mathbf{H}_{\text{pll}}(s)\mathbf{T}(\sin(\theta))\Delta \mathbf{u}_{\text{ca}} \end{cases} \quad (6)$$

式中: $\mathbf{H}(s)$ 为对应控制器生成的传递函数矩阵; $\mathbf{G}_{\text{pll}}(s)$ 为描述锁相环动态的传递函数。

交流侧二维开环(端口)序阻抗模型 $\mathbf{Z}_{\text{port}}(s)$ 和一维闭环(回路)序阻抗模型 $\mathbf{Z}_{\text{loop}}(s)$ 可以从对应的二维导纳模型 $\mathbf{Y}_{\text{port/loop}}(s)$ 提取部分项再求逆得到。

$$\begin{cases} \mathbf{A}_{\text{port}}(s)(-\Delta \mathbf{i}) = \mathbf{B}_{\text{port}}(s)\Delta \mathbf{u}_{\text{c}} \Rightarrow -\Delta \mathbf{i} = \mathbf{Y}_{\text{port}}(s)\Delta \mathbf{u}_{\text{c}} \\ \mathbf{A}_{\text{loop}}(s)(-\Delta \mathbf{i}) = \mathbf{B}_{\text{loop}}(s)\Delta \mathbf{u} \Rightarrow -\Delta \mathbf{i} = \mathbf{Y}_{\text{loop}}(s)\Delta \mathbf{u} \end{cases} \quad (7)$$

式中: $\Delta \mathbf{u}_{\text{c}}$ 表示图 1 中去除 L_g 直接在变流器端口加小扰动信号对应的矢量; $\mathbf{A}_{\text{port/loop}}(s)$ 和 $\mathbf{B}_{\text{port/loop}}(s)$ 为从三维 Toeplitz/对角传递函数矩阵运算结果中提取的二维对角块矩阵(可以证明非对角块矩阵为 $\mathbf{0}$)。

观察式(2)一式(7), 在求解 $\mathbf{Y}_{\text{port/loop}}(s)$ 时, 按式(8)消去中间变量 $\Delta \mathbf{v}_{\text{dc}}$ 和 $\Delta \mathbf{v}_a$ (仅求解 $\mathbf{Y}_{\text{loop}}(s)$ 时需要)。

$$\Delta \mathbf{v}_a = \Delta \mathbf{v} + \mathbf{Z}_g(s)\Delta \mathbf{i}_a, \Delta \mathbf{v}_{\text{dc}} = -\mathbf{Z}_c(s)\Delta \mathbf{i}_{\text{dc}} \quad (8)$$

综合式(2)一式(8), 在使用严格的潮流计算得到各稳态矢量(以并网点相位为参考相位)生成 Toeplitz 矩阵, 并由控制器、电感和电容依据频移关系生成传递函数矩阵后, 即可导出对应的二维矩阵 \mathbf{A} 、 \mathbf{B} 。受篇幅限制, \mathbf{A} 和 \mathbf{B} 的具体公式在此省略。

1.3 模型参数与工作点解耦的阻抗模型

对开环阻抗模型, 任一 f_p 的正序扰动及其互补频率 $f_p - 2f_1$ 的负序扰动满足

$$\begin{bmatrix} \mathbf{g}_{11} & \mathbf{g}_{12} \\ \mathbf{g}_{13} & \mathbf{g}_{14} \end{bmatrix} \begin{bmatrix} -\Delta \mathbf{i}_p \langle p \rangle \\ -\Delta \mathbf{i}_n \langle p-2 \rangle \end{bmatrix} = \begin{bmatrix} \mathbf{g}_{v1} & \mathbf{g}_{v2} \\ \mathbf{g}_{v3} & \mathbf{g}_{v4} \end{bmatrix} \begin{bmatrix} \Delta \mathbf{v}_p \langle p \rangle \\ \Delta \mathbf{v}_n \langle p-2 \rangle \end{bmatrix} \quad (9)$$

$$\begin{aligned} \mathbf{g}_{ik} &= \mathbf{a}_k^T \mathbf{x}, \mathbf{g}_{vk} = \mathbf{b}_k^T \mathbf{x} \quad (k=1, 2, 3, 4), \\ \mathbf{x} &= [1, \mathbf{i} \langle -1 \rangle, \mathbf{i} \langle 1 \rangle, \mathbf{u}_c \langle 1 \rangle, \mathbf{i}^2 \langle -1 \rangle, \mathbf{i} \langle -1 \rangle \mathbf{i} \langle 1 \rangle, \\ &\quad \mathbf{i} \langle -1 \rangle \mathbf{u}_c \langle 1 \rangle, \mathbf{i}^2 \langle 1 \rangle, \mathbf{i} \langle 1 \rangle \mathbf{u}_c \langle 1 \rangle, \mathbf{u}_c^2 \langle 1 \rangle, \mathbf{i}^2 \langle -1 \rangle \mathbf{i} \langle 1 \rangle, \\ &\quad \mathbf{i}^2 \langle -1 \rangle \mathbf{u}_c \langle 1 \rangle, \mathbf{i} \langle -1 \rangle \mathbf{u}_c^2 \langle 1 \rangle, \mathbf{i} \langle -1 \rangle \mathbf{i}^2 \langle 1 \rangle, \\ &\quad \mathbf{i} \langle -1 \rangle \mathbf{i} \langle 1 \rangle \mathbf{u}_c \langle 1 \rangle, \mathbf{i} \langle 1 \rangle^2 \mathbf{u}_c \langle 1 \rangle, \mathbf{i} \langle 1 \rangle \mathbf{u}_c^2 \langle 1 \rangle, \mathbf{u}_c^3 \langle 1 \rangle]^T_{18 \times 1}, \\ \mathbf{a}_k &= [\mathbf{a}_k^1 \cdots \mathbf{a}_k^{18}]^T_{18 \times 1}, \mathbf{b}_k = [\mathbf{b}_k^1 \cdots \mathbf{b}_k^{18}]^T_{18 \times 1} \end{aligned} \quad (10)$$

式中: \mathbf{x} 为由工作点 $\mathbf{i} \langle -1 \rangle$ 、 $\mathbf{i} \langle 1 \rangle$ 和 $\mathbf{u}_c \langle 1 \rangle = \mathbf{u}_c \langle -1 \rangle$ 的 0~3 阶项构成的矢量; \mathbf{a}_k 与 \mathbf{b}_k 为模型参数矢量, 是将 $s = j2\pi f_s = j\omega_s$ 代入各传递函数后与常数项的乘积。 $\mathbf{Y}_{\text{port}}(s)$ 的模型参数见附录 A。

对闭环阻抗模型, 其 \mathbf{b}_k 与开环阻抗模型一致, 但 \mathbf{a}_k 中出现了 L_g 与式(10)中 \mathbf{x} 的乘积项, 因此定义:

$$\mathbf{x}' = [\mathbf{x}; L_g \mathbf{x}] \quad (11)$$

将不同工况代入式(10)和式(11)生成 \mathbf{A} 和 \mathbf{B} , 即可按式(7)求解阻抗模型, 因此将基于式(9)一式(11)生成的阻抗模型定义为模型参数与工作点解耦的阻抗模型。

2 全工况阻抗模型的黑箱辨识

2.1 基本原理

考虑到开/闭环全工况阻抗模型结构的相似性, 本节仅阐述辨识 $\mathbf{Y}_{\text{port}}(s)$ 基本原理。由式(9)可得

$$\begin{cases} \mathbf{g}_{11}\Delta \mathbf{i}_p \langle p \rangle + \mathbf{g}_{12}\Delta \mathbf{i}_n \langle p-2 \rangle + \mathbf{g}_{v1}\Delta \mathbf{v}_p \langle p \rangle + \mathbf{g}_{v2}\Delta \mathbf{v}_n \langle p-2 \rangle = 0 \\ \mathbf{g}_{13}\Delta \mathbf{i}_p \langle p \rangle + \mathbf{g}_{14}\Delta \mathbf{i}_n \langle p-2 \rangle + \mathbf{g}_{v3}\Delta \mathbf{v}_p \langle p \rangle + \mathbf{g}_{v4}\Delta \mathbf{v}_n \langle p-2 \rangle = 0 \end{cases} \quad (12)$$

由阻抗/导纳模型量测结果得到

$$\begin{cases} \Delta \mathbf{i}_p \langle p \rangle = -Y_{pp}\Delta \mathbf{v}_p \langle p \rangle - Y_{pn}\Delta \mathbf{v}_n \langle p-2 \rangle \\ \Delta \mathbf{i}_n \langle p-2 \rangle = -Y_{np}\Delta \mathbf{v}_p \langle p \rangle - Y_{nn}\Delta \mathbf{v}_n \langle p-2 \rangle \end{cases} \quad (13)$$

式中, Y_{pp} 、 Y_{pn} 、 Y_{np} 、 Y_{nn} 为注入一组扰动信号得到的 $\mathbf{Y}_{\text{port}}(s)$ 的 4 个量测值。将式(10)和式(13)代入式(12)得到

$$\begin{cases} -Y_{pp}\mathbf{a}_1^T \mathbf{x} - Y_{np}\mathbf{a}_2^T \mathbf{x} + \mathbf{b}_1^T \mathbf{x} = 0 \\ -Y_{pn}\mathbf{a}_1^T \mathbf{x} - Y_{nn}\mathbf{a}_2^T \mathbf{x} + \mathbf{b}_2^T \mathbf{x} = 0 \\ -Y_{pp}\mathbf{a}_3^T \mathbf{x} - Y_{np}\mathbf{a}_4^T \mathbf{x} + \mathbf{b}_3^T \mathbf{x} = 0 \\ -Y_{pn}\mathbf{a}_3^T \mathbf{x} - Y_{nn}\mathbf{a}_4^T \mathbf{x} + \mathbf{b}_4^T \mathbf{x} = 0 \end{cases} \quad (14)$$

按以下两步求解同一组扰动频率的模型参数。

1) 测量 N_1 个工况, 求解齐次线性方程组。

$$\mathbf{M}_1^T \boldsymbol{\rho} = \mathbf{0} \quad (15)$$

其中

$$\mathbf{M}_1 = \begin{bmatrix} -Y_{pp} \mathbf{x}^T & -Y_{np} \mathbf{x}^T & \mathbf{x}^T \end{bmatrix}_{54 \times N_1}^T \quad (16)$$

任选方程(15)的两个基础解系 $\boldsymbol{\rho}_1$ 和 $\boldsymbol{\rho}_2$, 提取相应的元素作为部分模型参数(具体原理可参考文献[20])。

$$\boldsymbol{\rho}_1 = \begin{bmatrix} \mathbf{a}_1^T & \mathbf{a}_2^T & \mathbf{b}_1^T \end{bmatrix}_{54 \times 1}^T, \boldsymbol{\rho}_2 = \begin{bmatrix} \mathbf{a}_3^T & \mathbf{a}_4^T & \mathbf{b}_3^T \end{bmatrix}_{54 \times 1}^T \quad (17)$$

2) 测量 N_2 个工况, 求解非齐次线性方程组。

$$\mathbf{x}^T \mathbf{b}_2 = \mathbf{M}_2^T \begin{bmatrix} \mathbf{a}_1^T & \mathbf{a}_2^T \end{bmatrix}^T, \mathbf{x}^T \mathbf{b}_4 = \mathbf{M}_2^T \begin{bmatrix} \mathbf{a}_3^T & \mathbf{a}_4^T \end{bmatrix}^T \quad (18)$$

其中

$$\mathbf{M}_2 = \begin{bmatrix} Y_{pn} \mathbf{x}^T & Y_{nn} \mathbf{x}^T \end{bmatrix}_{36 \times N_2}^T \quad (19)$$

理论上可以取 $N_2 = N_1$, 且为保证足够高的辨识精度, N_1 存在近似的下限(注意不是上限^[21-22])。

$$N_1 \geq 3N_{x/x'} - 2 \quad (20)$$

式中, $N_{x/x'}$ 为矢量阶数, 本文中 $N_x = 18$, $N_{x'} = 36$ 。

将上述思路由一组互补频率推广到全频率范围, 即可得到宽频带全工况导纳模型。考虑到辨识出的模型参数与附录A中的实际理论模型参数矢量是同一齐次线性方程组的不同特解, 所提方法不需要对控制器具体结构和参数进行精确辨识。此外, 尽管本文分析 N_1 、 N_2 的理论下限是针对图1所示的控制回路, 但“逐级”增加 \mathbf{x}/\mathbf{x}' 中工作点的高阶项, 所提方法能够可靠地推广到一般黑箱系统。

2.2 辨识结果

依据2.1节的原理, 分别随机选取52和106个稳定的工况, 使用Matlab求解开/闭环全工况导纳模型的模型参数。图2和图3分别展示了对两个模型第53和第107个工况从-49.5至149.5 Hz(步长1 Hz)频率响应的预测结果。对每个传递函数, 最大的幅值响应误差均小于 10^{-3} dB, 辨识精度极高。

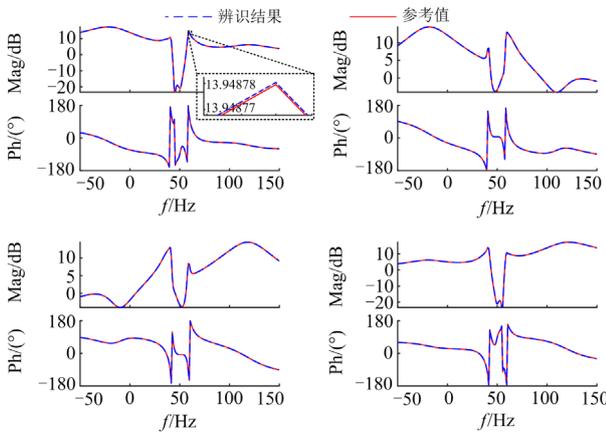


图2 $Y_{port}(s)$ 辨识结果

Fig. 2 Identification of $Y_{port}(s)$

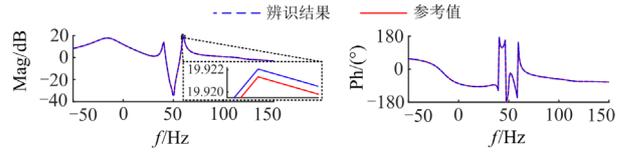


图3 $Y_{loop}(s)/Y_{pp}(s)$ 辨识结果

Fig. 3 Identification of $Y_{loop}(s)/Y_{pp}(s)$

为达到对任意工况良好的预测结果, 求解模型参数时应调整 i_{load} 、 i_q^* 、 u_t 和 L_g (仅对开环导纳模型) 改变系统工作点。表2对比了 $N_1 = 30$ 、60、90、120 求解模型参数, 辨识同一闭环 $Y_{pp}(s)$ 幅值的总体标准差, 发现训练样本集越大, 模型的泛化能力越强, 辨识精度越高, 这符合一般认知。

表2 辨识同一 $Y_{pp}(s)$ 的精度对比

Table 2 Precision comparison of identifying the same $Y_{pp}(s)$

N_1	30	60	90	120
总体标准差(幅值)/%	8.7	3.3	0.16	0.03

3 基于全工况阻抗模型的稳定性分析

3.1 稳定性判据

考虑到闭环系统的模式体现在闭环回路阻抗模型的分子多项式中, 本文使用基于传递函数频率响应对数导数的稳定性辨识不稳定模式^[23-24]。

将 $s = j\omega$ 代入 $Z_{pp}(s) = 1/Y_{pp}(s)$ 化为零极点形式, 如式(21)所示。

$$Z_{pp}(j\omega) = \prod_{i=1}^{n_z} a_{zi}(j\omega - Z_i) / \prod_{i=1}^{n_p} a_{pi}(j\omega - P_i) \quad (21)$$

式中: a 为常数增益; Z/P(包括下标)表示零/极点; n_z 、 n_p 分别为零、极点数量。

提取式(21)的一个基本单元 $g_z(\omega) = \alpha_z(j\omega - \lambda_z)$, $\lambda_z = \alpha_z + j\omega_z$, 对数导数 $D_L(\cdot)$ 定义为

$$D_L(g_z) = d \log(g_z) / d\omega = d(g_z) / (g_z d\omega) = j / (j\omega - \lambda_z) = j / [-\alpha_z + j(\omega - \omega_z)] \quad (22)$$

分离 $D_L(g_z)$ 的实、虚部并分别求二者关于 ω 的导数, 易知

$$\begin{cases} \text{Re}[D_L(g_z)]|_{\omega=\omega_z} = 0 \\ \text{Im}[D_L(g_z)]|_{\omega=\omega_z} = -1/\alpha_z \\ d\{\text{Re}[D_L(g_z)]\}/d\omega|_{\omega=\omega_z} = 1/\alpha_z^2 \\ d\{\text{Im}[D_L(g_z)]\}/d\omega|_{\omega=\omega_z} = 0 \\ d^2\{\text{Re}[D_L(g_z)]\}/d\omega^2|_{\omega=\omega_z} = 0 \\ d^2\{\text{Im}[D_L(g_z)]\}/d\omega^2|_{\omega=\omega_z} = 2/\alpha_z^3 \end{cases} \quad (23)$$

式(23)说明,若 $\alpha > 0$,对 $\omega = \omega_z$, $\text{Re}[D_L(g_z)]$ 由负向正过零且 $\text{Im}[D_L(g_z)]$ 存在极小值。对数导数确保了分子与分母多项式的对偶性,且当单一 ω 附近不存在多个零/极点时,各基本单元的耦合很小。因此,在所关心的频率范围内,存在一 ω_z ,满足式(24)即判定系统失稳。

$$\text{Re}[D_L(Z_{pp}(\omega_z))] < 0 \ \& \ \& \ \text{Re}[D_L(Z_{pp}(\omega_z + \omega_0))] > 0 \ \& \ \& \ 0.5\{\text{Im}[D_L(Z_{pp}(\omega_z))] + \text{Im}[D_L(Z_{pp}(\omega_z + \omega_0))]\} < 0 \quad (24)$$

3.2 不同短路比条件下系统振荡安全运行域

考虑到变流器与弱电网的交互作用是诱发振荡问题的典型场景之一,进一步在变量器额定容量 $S_0 = 100 \text{ kVA}$ 内,按 $S_0/10$ 调整并网点有功/无功(P/Q)预期出力。图4展示了 L_g 为0.6、1.0 mH两种短路比条件下系统的振荡安全运行域,对后者,选择四组边界内/外的出力组合在PSCAD中仿真。图5的仿真结果初步说明了所评估振荡安全运行域的准确性和相关方法的可行性。

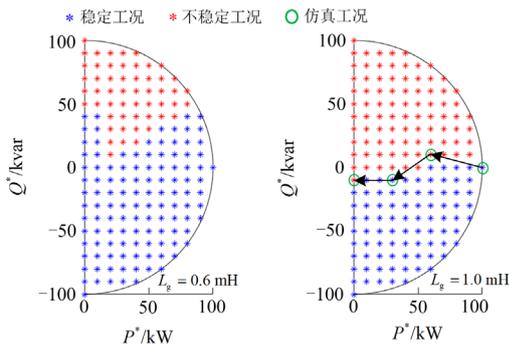


图4 系统振荡安全运行域

Fig. 4 Safe operating range of system regarding oscillation

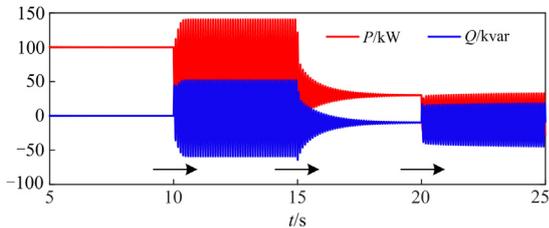


图5 PSCAD 仿真结果

Fig. 5 Simulations using PSCAD

4 讨论

4.1 已有工作潜在失效的原因

文献[21-22]与本文使用相同结构的并网变流器系统时,尽管可以通过更复杂的辨识流程从理论上减少了量测工况数量,但“未考虑工作点三阶项,

仅使用约10组^[19]或约28组^[20]工况的量测数据辨识任一工况阻抗模型频率响应”的结论理论上是错误的。然而,文献[21-22]却显示其显示辨识结果良好,潜在原因如下:

1) 文献[21-22]使用的控制器参数恰好使各三阶项与模型参数的乘积对阻抗模型的贡献很小;

2) 采用少样本集可以求解出方程(15)的两个基础解系进而求出模型参数,但增大样本集却可能导致 M_1 满秩,即文献[21-22]的求解结果出现了类似“过拟合”的现象。

因此,应正确认识本文所涉及的概念和原理以提高黑箱辨识方法的可靠性和精度。

4.2 所提方法在其他对象中的适用性

本文得出“考虑工作点三阶项辨识全工况交流阻抗模型”的结论,对三相两电平变流器这一新能源并网系统中的常用装备应是合理的:送端变流器交流阻抗模型不受直流侧耦合影响,而构网型变流器不使用锁相环,均会使所需工作点最高项降低。然而,对存在更复杂谐波耦合关系的模块化多电平变流器^[25-27]或背靠背型全功率变流器,可以预见辨识全工况阻抗模型将使用工作点的更高阶项,这既会增加辨识的计算量,也会影响辨识的精度(M 的病态程度加剧)。因此,理解本文所提方法的思路,寻找耦合路径最小的基本组件进行辨识并用于稳定性分析,是潜在的改进方向。

4.3 应用人工神经网络的必要性

文献[19-20]设计深度神经网络辨识了不考虑直流侧耦合的两电平变流器交流侧全工况模型,普遍需要约100个工况的频率响应且训练网络的时间为分钟级,远高于本文的计算成本。对本课题应用深度学习方法的必要性,从以下两方面进行讨论:

1) 设计神经网络结构或超参数时,应参考本文基于理论模型得到的结论;

2) 对4.2节提及的更复杂辨识对象,基于人工神经网络的方法可能会比基于最小二乘理论的方法有更优越的表现。

5 结论

1) 基于谐波线性化推导了三相两电平变流器全工况交流开/闭环阻抗模型,其中直流动态引入了工作点三阶项,且闭环阻抗模型所需模型参数多于开环阻抗模型。

2) 揭示了单变流器并网系统全工况阻抗模型的黑箱辨识机理,指出可以使用约50组工况的量测数据辨识开环阻抗模型参数,或使用约100组工况的量测数据辨识闭环阻抗模型参数,进而导出任意

工况阻抗模型频率响应, 并可用于系统振荡安全工作域的快速评估。

3) 讨论了阻抗模型理论辨识方法的合理性、适用性和优越性, 以推动阻抗分析法的工程应用。

附录 A

为简化表示, 公式中 $h(s) = k_p + k_i / s$, $y^c(s) = 1/sC$, $z^1(s) = sL$; 省略 Laplace 算子 s ; 下标 p、n、z 分别表示对应传递函数矩阵的(3,3)、(2,2)、(1,1)元素。

$$\begin{aligned}
a_1^1 &= 2h_z^{cc} u_{dc}^{*2} y_z^c + 2u_{dc}^{*2} y_z^c z_n^f, \\
a_1^2 &= 3h_z^{dc} h_z^{cc2} u_{dc}^* + 3h_z^{dc} h_z^{cc} u_{dc}^* z_n^f, \\
a_1^3 &= 3h_z^{dc} h_z^{cc} u_{dc}^* z_n^f + j6\pi f_1 L_f h_z^{dc} h_z^{cc} u_{dc}^*, \\
a_1^4 &= 3h_z^{dc} h_z^{cc} u_{dc}^* + 4h_z^{cc} h_z^{pll} u_{dc}^* y_z^c + 4h_z^{pll} u_{dc}^* y_z^c z_n^f, \\
a_1^6 &= j24\pi^2 f_1^2 L_f^2 + j12\pi f_1 L_f h_z^{cc}, \\
a_1^7 &= -j12\pi f_1 L_f + 6h_z^{dc} h_z^{cc2} h_z^{pll} u_{dc}^* + 6h_z^{dc} h_z^{cc} h_z^{pll} u_{dc}^* z_n^f, \\
a_1^9 &= -6h_z^{cc} + j12\pi f_1 L_f + 6h_z^{dc} h_z^{cc} h_z^{pll} u_{dc}^* z_n^f + \\
&\quad j12\pi f_1 L_f h_z^{dc} h_z^{cc} h_z^{pll} u_{dc}^*, \\
a_1^{10} &= 6 + 6h_z^{dc} h_z^{cc} h_z^{pll} u_{dc}^*, a_1^{13} = -j24\pi f_1 L_f h_z^{pll}, \\
a_1^{15} &= 48\pi^2 f_1^2 L_f^2 h_z^{pll} + j24\pi f_1 L_f h_z^{cc} h_z^{pll}, \\
a_1^{17} &= j24\pi f_1 L_f h_z^{pll} - 12h_z^{cc} h_z^{pll}, a_1^{18} = 12h_z^{pll}, \\
a_1^5 &= a_1^8 = a_1^{11} = a_1^{12} = a_1^{14} = a_1^{16} = 0. \\
a_2^2 &= -j6\pi f_1 L_f h_z^{dc} u_{dc}^* h_z^{cc} - 3h_z^{dc} u_{dc}^* h_z^{cc2}, a_2^4 = 3h_z^{dc} u_{dc}^* h_z^{cc}, \\
a_2^5 &= -j24\pi^2 f_1^2 L_f^2 + j12\pi f_1 L_f h_z^{cc}, \\
a_2^7 &= -j24\pi f_1 L_f - 6h_z^{cc} - j12\pi f_1 L_f h_z^{dc} h_z^{pll} u_{dc}^* h_z^{cc} - \\
&\quad 6h_z^{dc} h_z^{pll} u_{dc}^* h_z^{cc2}, \\
a_2^{10} &= 6 + 6h_z^{dc} h_z^{pll} u_{dc}^* h_z^{cc}, \\
a_2^{12} &= -48\pi^2 f_1^2 L_f^2 h_z^{pll} + j24\pi f_1 L_f h_z^{cc} h_z^{pll}, \\
a_2^{13} &= -j48\pi f_1 L_f h_z^{pll} - 12h_z^{pll} h_z^{cc}, a_2^{18} = 12h_z^{pll}, \\
a_2^1 &= a_2^3 = a_2^6 = a_2^8 = a_2^9 = a_2^{11} = a_2^{14} = a_2^{15} = a_2^{16} = a_2^{17} = 0. \\
a_3^3 &= j6\pi f_1 L_f h_z^{dc} u_{dc}^* h_z^{cc} - 3h_z^{dc} u_{dc}^* h_z^{cc2}, a_3^4 = 3h_z^{dc} u_{dc}^* h_z^{cc}, \\
a_3^8 &= -24\pi^2 f_1^2 L_f^2 - j12\pi f_1 L_f h_z^{cc}, \\
a_3^9 &= -6h_z^{cc} + j24\pi f_1 L_f + j12\pi f_1 L_f h_z^{dc} h_z^{pll} u_{dc}^* h_z^{cc} - \\
&\quad 6h_z^{dc} h_z^{pll} u_{dc}^* h_z^{cc2}, \\
a_3^{10} &= 6 + 6h_z^{dc} h_z^{pll} u_{dc}^* h_z^{cc}, \\
a_3^{16} &= -48\pi^2 f_1^2 L_f^2 h_z^{pll} - j24\pi f_1 L_f h_z^{cc} h_z^{pll}, \\
a_3^{17} &= j48\pi f_1 L_f h_z^{pll} - 12h_z^{pll} h_z^{cc}, a_3^{18} = 12h_z^{pll}, \\
a_3^1 &= a_3^2 = a_3^5 = a_3^6 = a_3^7 = a_3^{11} = a_3^{12} = a_3^{13} = a_3^{14} = a_3^{15} = 0.
\end{aligned}$$

$$\begin{aligned}
a_4^1 &= 2h_z^{cc} u_{dc}^{*2} y_z^c + 2u_{dc}^{*2} y_z^c z_p^f, \\
a_4^2 &= 3h_z^{dc} h_z^{cc} u_{dc}^* z_p^f - j6\pi f_1 L_f h_z^{dc} h_z^{cc} u_{dc}^*, \\
a_4^3 &= 3h_z^{dc} h_z^{cc2} u_{dc}^* + 3h_z^{dc} h_z^{cc} u_{dc}^* z_p^f, \\
a_4^4 &= 3h_z^{dc} h_z^{cc} u_{dc}^* + 2h_z^{pll} u_{dc}^{*2} y_z^c z_p^f, \\
a_4^6 &= 24\pi^2 f_1^2 L_f^2 - j12\pi f_1 L_f h_z^{cc}, \\
a_4^7 &= -6h_z^{cc} - j12\pi f_1 L_f + 6h_z^{dc} h_z^{cc} h_z^{pll} u_{dc}^* z_p^f - \\
&\quad j12\pi f_1 L_f h_z^{dc} h_z^{cc} h_z^{pll} u_{dc}^*, \\
a_4^9 &= j12\pi f_1 L_f + 6h_z^{dc} h_z^{cc2} h_z^{pll} u_{dc}^* + 6h_z^{dc} h_z^{cc} h_z^{pll} u_{dc}^* z_p^f, \\
a_4^{10} &= 6 + 6h_z^{dc} h_z^{cc} h_z^{pll} u_{dc}^*, a_4^{12} = -12h_z^{cc} h_z^{pll} - j24\pi f_1 L_f h_z^{pll}, \\
a_4^{14} &= -j24\pi f_1 L_f h_z^{cc} h_z^{pll} + 48\pi^2 f_1^2 L_f^2 h_z^{pll}, \\
a_4^{17} &= j24\pi f_1 L_f h_z^{pll}, a_4^{18} = 12h_z^{pll}, \\
a_4^5 &= a_4^8 = a_4^{11} = a_4^{13} = a_4^{16} = 0. \\
b_1^1 &= 2y_z^c u_{dc}^{*2}, \\
b_1^2 &= -2h_z^{pll} y_z^c h_z^{cc} u_{dc}^{*2} + 3h_z^{dc} h_z^{cc} u_{dc}^* + j4\pi f_1 L_f h_z^{pll} y_z^c u_{dc}^{*2}, \\
b_1^3 &= 3h_z^{dc} h_z^{cc} u_{dc}^*, b_1^4 = 2h_z^{pll} y_z^c u_{dc}^{*2}, \\
b_1^5 &= j6\pi f_1 L_f h_z^{dc} h_z^{pll} h_z^{cc} u_{dc}^* - 3h_z^{dc} h_z^{pll} h_z^{cc2} u_{dc}^*, \\
b_1^6 &= -j6\pi f_1 L_f h_z^{dc} h_z^{pll} h_z^{cc} u_{dc}^* - 3h_z^{dc} h_z^{pll} h_z^{cc2} u_{dc}^*, \\
b_1^9 &= 6h_z^{dc} h_z^{pll} h_z^{cc} u_{dc}^*, b_1^{11} = -48\pi^2 f_1^2 L_f^2 h_z^{pll}, \\
b_1^{12} &= j12\pi f_1 L_f h_z^{pll}, b_1^{13} = -6h_z^{pll}, \\
b_1^{15} &= -j36\pi L_f f_1 h_z^{pll}, b_1^{17} = 6h_z^{pll}, \\
b_1^7 &= b_1^8 = b_1^{10} = b_1^{14} = b_1^{16} = b_1^{18} = 0. \\
b_2^2 &= -j4\pi f_1 L_f h_z^{pll} y_z^c u_{dc}^{*2} + 2h_z^{pll} y_z^c h_z^{cc} u_{dc}^{*2}, b_2^4 = 2h_z^{pll} y_z^c u_{dc}^{*2}, \\
b_2^5 &= -j6\pi f_1 L_f h_z^{dc} h_z^{pll} h_z^{cc} u_{dc}^* + 3h_z^{dc} h_z^{pll} h_z^{cc2} u_{dc}^*, \\
b_2^6 &= j6\pi f_1 L_f h_z^{dc} h_z^{pll} h_z^{cc} u_{dc}^* + 3h_z^{dc} h_z^{pll} h_z^{cc2} u_{dc}^*, \\
b_2^7 &= 6h_z^{dc} h_z^{pll} h_z^{cc} u_{dc}^*, b_2^{11} = 48\pi^2 f_1^2 L_f^2 h_z^{pll}, \\
b_2^{12} &= -j12\pi f_1 L_f h_z^{pll}, b_2^{13} = 6h_z^{pll}, \\
b_2^{15} &= j36\pi f_1 L_f h_z^{pll}, b_2^{17} = -6h_z^{pll}, \\
b_2^1 &= b_2^3 = b_2^8 = b_2^9 = b_2^{10} = b_2^{14} = b_2^{16} = b_2^{18} = 0. \\
b_3^3 &= j4\pi f_1 L_f h_z^{pll} y_z^c u_{dc}^{*2} + 2h_z^{pll} y_z^c h_z^{cc} u_{dc}^{*2}, b_3^4 = 2h_z^{pll} y_z^c u_{dc}^{*2}, \\
b_3^6 &= -j6\pi f_1 L_f h_z^{dc} h_z^{pll} h_z^{cc} u_{dc}^* + 3h_z^{dc} h_z^{pll} h_z^{cc2} u_{dc}^*, \\
b_3^8 &= j6\pi f_1 L_f h_z^{dc} h_z^{pll} h_z^{cc} u_{dc}^* + 3h_z^{dc} h_z^{pll} h_z^{cc2} u_{dc}^*, \\
b_3^9 &= 6h_z^{dc} h_z^{pll} h_z^{cc} u_{dc}^*, b_3^{13} = -6h_z^{pll}, \\
b_3^{14} &= 48\pi^2 f_1^2 L_f^2 h_z^{pll}, b_3^{15} = -j36\pi f_1 L_f h_z^{pll}, \\
b_3^{16} &= j12\pi f_1 L_f h_z^{pll}, b_3^{17} = 6h_z^{pll}, \\
b_3^1 &= b_3^2 = b_3^5 = b_3^7 = b_3^{10} = b_3^{11} = b_3^{12} = b_3^{18} = 0.
\end{aligned}$$

$$\begin{aligned}
b_4^1 &= 2y_z^c u_{dc}^{*2}, \quad b_4^2 = 3h_z^{dc} h_z^{cc} u_{dc}^*, \\
b_4^3 &= -j4\pi f_1 L_f h_z^{pll} y_z^c u_{dc}^{*2} - 2h_z^{pll} y_z^c h_z^{cc} u_{dc}^{*2} + 3h_z^{dc} h_z^{cc} u_{dc}^*, \\
b_4^4 &= 2h_z^{pll} y_z^c u_{dc}^{*2}, \\
b_4^6 &= j6\pi f_1 L_f h_z^{dc} h_z^{pll} h_z^{cc} u_{dc}^* - 3h_z^{dc} h_z^{pll} h_z^{cc2} u_{dc}^*, \\
b_4^7 &= 6h_z^{dc} h_z^{pll} h_z^{cc} u_{dc}^*, \\
b_4^8 &= -j6\pi f_1 L_f h_z^{dc} h_z^{pll} h_z^{cc} u_{dc}^* - 3h_z^{dc} h_z^{pll} h_z^{cc2} u_{dc}^*, \quad b_4^{13} = 6h_z^{pll}, \\
b_4^{14} &= -48\pi^2 f_1^2 L_f^2 h_z^{pll}, \quad b_4^{15} = j36\pi f_1 L_f h_z^{pll}, \\
b_4^{16} &= -j12\pi f_1 L_f h_z^{pll}, \quad b_4^{17} = -6h_z^{pll}, \\
b_4^5 &= b_4^9 = b_4^{10} = b_4^{11} = b_4^{12} = b_4^{18} = 0.
\end{aligned}$$

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作者简介:

赵崇滨(1997—), 男, 博士研究生, 研究方向为电能质量分析与控制、变流器驱动的电力系统稳定性线性/非线性建模与分析; E-mail: zhaocb19@mails.tsinghua.edu.cn

姜齐荣(1968—), 男, 通信作者, 博士, 教授, 研究方向为柔性输配电技术、电能质量分析与控制、新能源发电/分布式发电技术。E-mail: qrjiang@tsinghua.edu.cn

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